Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage

Paul Denholm, Wesley Cole, and Nate Blair

National Renewable Energy Laboratory

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-85878
September 2023

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Suggested Citation
Denholm, Paul, Wesley Cole, and Nate Blair. 2023. *Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-85878. https://www.nrel.gov/docs/fy23osti/85878.pdf.

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Golden, CO 80401
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Acknowledgments

The authors would like to thank the following individuals for their contributions. Editing and other communications support was provided by Liz Breazeale, Madeline Geocaris, and Mike Meshek. Helpful review and comments were provided by Sam Baldwin, Yonghong Chen, Stuart Cohen, Jaquelin Cochran, Udi Helman, Caitlin Murphy, Jess Kuna, David Palchak, Mark Ruth, and Greg Stark. Data for several figures was provided by Kevin Cardin and Alex Dombrowsky from Astrapé Consulting.

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Strategic Analysis Team, U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office, and U.S. Department of Energy Office of Electricity. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Preface

This report builds on the National Renewable Energy Laboratory's Storage Futures Study, a research project from 2020 to 2022 that explored the role and impact of energy storage in the evolution and operation of the U.S. power sector. The Storage Futures Study examined the potential impact of energy storage technology advancement on the deployment of utility-scale storage and the adoption of distributed storage and the implications for future power system infrastructure investment and operations. The research findings and supporting data were published as a series of seven publications available at https://www.nrel.gov/analysis/storage-futures.html.

This report is a continuation of the Storage Futures Study and explores the factors driving the transition from recent storage deployments with four or fewer hours to deployments of storage with greater than four hours. The report specifically builds on the first publication in the Storage Futures Study series, *The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System*, that established a conceptual framework of roles and opportunities for new, cost-competitive stationary energy storage over the course of four phases of current and potential future storage deployment. This latest publication delves into Phases 2 and 3 when solar photovoltaics (PV) and storage increase the value of each other, and lower costs and technology improvements enable storage to be cost-competitive while serving longer-duration applications.

The Storage Futures Study series provides data and analysis in support of the U.S. Department of Energy's Energy Storage Grand Challenge, a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage. The Energy Storage Grand Challenge employs a use case framework to ensure storage technologies can cost-effectively meet specific needs, and it incorporates a broad range of technologies in several categories: electrochemical, electromechanical, thermal, flexible generation, flexible buildings, and power electronics. More information, any supporting data associated with this report, links to other reports in the series, and other information about the broader study are available at https://www.nrel.gov/analysis/storage-futures.html.

List of Acronyms

ATB	Annual Technology Baseline
CAISO	California Independent System Operator
EIA	U.S. Energy Information Administration
ELCC	effective load carrying capability
ERCOT	Electric Reliability Council of Texas
FRCC	Florida Reliability Coordinating Council
GW	gigawatts
ISO	independent system operator
ISO-NE	ISO New England
kWh	kilowatt-hour (*either* a unit of energy *or* a unit of storage capacity)
kw-yr	kilowatt of capacity available for 1 year
MISO	Midcontinent Independent System Operator
MW	megawatts
MWh	megawatt-hour (energy)
MW-hr	megawatt of capacity available for 1 hour
NREL	National Renewable Energy Laboratory
NYISO	New York Independent System Operator
PJM	PJM interconnection (regional transmission organization)
PSH	pumped storage hydropower
PV	photovoltaics
SPP	Southwest Power Pool

Executive Summary

By the end of 2022 about 9 GW of energy storage had been added to the U.S. grid since 2010, adding to the roughly 23 GW of pumped storage hydropower (PSH) installed before that. Of the new storage capacity, more than 90% has a duration of 4 hours or less, and in the last few years, Li-ion batteries have provided about 99% of new capacity.

There is strong and growing interest in deploying energy storage with greater than 4 hours of capacity, which has been identified as potentially playing an important role in helping integrate larger amounts of renewable energy and achieving heavily decarbonized grids. Analysis in the Storage Futures Study identified economic opportunities for hundreds of gigawatts of 6–10 hour storage even without new policies targeted at reducing carbon emissions. When considering storage's role in decarbonization and enabling renewable energy, that potential could be even greater.

Despite the large potential, there is still significant uncertainty regarding the role of longer-duration storage, and the possible technologies that can compete with Li-ion batteries in a shift toward longer durations.

Historically, 4-hour storage has been well-suited to providing capacity during summer peaks in many U.S. regions, which has led to several wholesale market regions adopting a "4-hour capacity rule." This rule allows storage with at least 4 hours of duration to receive full compensation in capacity markets or in other contracts for provision of firm capacity (with no additional capacity revenues for longer durations). This rule, along with limited additional energy arbitrage value for longer durations and the cost structure of Li-ion batteries, has created a disincentive for durations beyond 4 hours. Based in part on this rule, in 2021 and 2022, about 40% of storage capacity installed was exactly 4 hours of duration, and less than 6% had durations of greater than 4 hours.

The ability of 4-hour storage to meet peak demand during the summer is further enhanced with greater deployments of solar energy. However, the addition of solar, plus changing weather and electrification of building heating, may lead to a shift to *net* winter demand peaks, which are often longer than can be effectively served by 4-hour storage. Several regions of the United States (regions in the Southeast and Texas) have shifted to net winter peaks in recent years. As regions change rules for storage capacity credit, this could ultimately provide greater incentive for longer-duration storage in the coming years. Provision of additional services such as transmission congestion relief and resilience could also increase opportunities for longer-duration storage.

Several storage technology options have the potential to achieve lower per-unit of energy storage costs and longer service lifetimes. These characteristics could offset potentially higher power-related cost and lower efficiency to achieve life cycle cost parity at some duration. However, the new technologies must compete against the well-established Li-ion technology, with its expected cost reductions and potential ability to achieve longer durations. Cost parity for new technologies will likely depend on deployments at scale, and points to the potential role of policies to enable a diverse portfolio of cost-optimal storage technologies with longer durations to support the evolving grid.

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1 Introduction

After a multidecade hiatus, there is growing deployment of grid-scale energy storage in the United States, as well as projections of accelerated growth. Much of the storage deployed in the past few years (and proposed for deployment in the next few years) is in the form of lithium-ion batteries typically with 4 hours or less of duration. However, there is growing interest in the deployment of energy storage with greater than 4 hours of capacity, which has been identified as potentially playing an important role in helping integrate larger amounts of renewable energy and achieving heavily decarbonized grids.[1,2,3]

Despite this interest, there are significant uncertainties about which of technologies might achieve cost-effective deployment at scale, as well as the actual value of services longer-duration storage might provide, particularly when competing against shorter-duration technologies now being deployed. Currently, 4-hour storage is well-suited to providing capacity during summer peaks, and the ability for 4-hour storage to serve summer peaks is enhanced with greater deployments of solar energy.[4] However, changing weather, deployment of solar energy, and electrification may lead to conditions where winter demand peaks are the primary driver of resource adequacy needs. Winter peaks are often longer than can be effectively served by 4-hour storage. The timing of this shift is uncertain, as is the role of various technologies that have the potential to provide cost-effective storage with durations beyond 4 hours.

In this work, we explore the opportunities and challenges that could lead to a shift from 4-hour to longer-duration energy storage. While much of this discussion may be relevant internationally, the focus of this paper is exclusively on the U.S. power grid, particularly due to the very specific rules for valuing and compensating capacity in wholesale electricity markets. The paper structure and goals are as follows:

Section 2 discusses why Li-ion batteries with 4 hours or less duration have been the dominant technology deployed in the last several years. It provides an overview of the framework for economic deployment of energy storage and discusses how costs and benefits can be compared, particularly in the context of storage duration.

Section 3 discusses a possible pathway for a transition to moving beyond 4-hour storage, based on factors including the declining value of shorter-duration storage to provide capacity, particularly as net demand peaks shift to winter. Our focus is on the transition that will occur in the relatively near term, and not the longer term transition, including scenarios of deep decarbonization.

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[1] Mai, T., et al. (2014). "Renewable Electricity Futures for the United States" *IEEE Transactions on Sustainable Energy*. 5(2) 372-378.

[2] Guerra, O. J., J. Eichman, P. Denholm. (2021). "Optimal Energy Storage Portfolio for High and Ultrahigh Carbon-Free and Renewable Power Systems." *Energy & Environmental Science* 14, 5132–5146.

[3] N. A. Sepulveda, J. D. Jenkins, F. J. de Sisternes, R. K. Lester, The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule* 2, 2403–2420 (2018).

[4] Frazier, A. W., W. Cole, P. Denholm, S. Machen, N. Gates, N. Blair. (2021) *Storage Futures Study: Economic Potential of Diurnal Storage in the U.S. Power Sector*. NREL/TP-6A20-77449.

Section 4 discusses a possible technology transition beyond Li-ion for stationary applications and the importance of capacity- and energy-related costs.

Caveats About Defining Storage Duration

While we briefly discuss different technology classes and options in Section 4, our approach is largely technology neutral, and the primary distinguishing characteristic we focus on is duration, where the impact of other factors such as efficiency is discussed in Section 4. We define duration as the length of time a storage system can generate at full output before needing to recharge. We acknowledge there are a variety of definitions of "long duration" and this work is not intended to discuss the transition to any particular duration, but instead explore the landscape of moving beyond 4-hour durations that represent a large fraction of current installations.[5]

[5] Denholm, P., W.J. Cole, A.W. Frazier, K. Podkaminer, N. Blair. (2021). *The Challenges of Defining Long Duration Energy Storage*. NREL/TP-6A40-80583.

2 Four Hours or Less: Drivers of Recent Storage Deployments

To understand the potential opportunities for moving past 4 hours, we first explore why 4 hours or less has provided the majority of the market for stationary storage in the past decade. The United States has about 23 GW of pumped storage hydropower (PSH), largely completed before 2000 (and most of these plants have 8 hours or more of storage). Table 1 shows deployments of utility-scale electrical energy storage technologies in the United States from 2010–2022.[6] This table does not include storage with capacity of less than 1 MW, including behind-the-meter storage, but does include storage capacity associated with hybrid plants that combine storage with solar or wind.[7] It also does not include thermal storage deployed in concentrating solar plants or distributed thermal storage used for heating and cooling. Of the battery capacity where the technology type was identified, over 99% was listed as Li-ion in 2021 and 2022.

Table 1. Annual Deployments of Energy Storage in the United States Starting in 2010

Year	Power (MW)	Weighted Avg. Duration (Hours)	Notes
2010–2014	210	0.7	Total power capacity includes 42 MW of PSH completed in 2012, but the duration average does not include this plant.
2015	150	0.5	
2016	200	1.3	
2017	130	2.2	
2018	220	2.3	
2019	190	2.7	
2020	500	1.2	Data are dominated by a single 250-MW 1-hr plant.
2021	3,380	2.9	99.9% of capacity is listed as Li-ion.
2022	4,160	2.7	99.7% of capacity is listed as Li-ion.
Total	**9,140**	**2.6**	As of June 2023 EIA shows another 1,763 MW of batteries competed and 7,165 under construction. Of the completed projects, only about 20% include duration data, but the average of these was below 2 hours.

Figure 1 shows the total installed capacity from 2010 to 2022 by duration shown in 1-hour increments. We also note the fraction of that capacity reported to have exactly a whole number duration; for example, a total of 1,100 MW of 1-hour storage is listed and 1,800 MW of storage between 1 and 2 hours.

[6] Rounded to the nearest 10 MW. Data from U.S. Energy Information Administration (EIA) Form 860M from June 2023, https://www.eia.gov/electricity/data/eia860m/.
[7] R. H. Wiser, et al. (2020). Hybrid Power Plants: Status of Installed and Proposed Projects. https://emp.lbl.gov/publications/hybrid-power-plants-status-installed

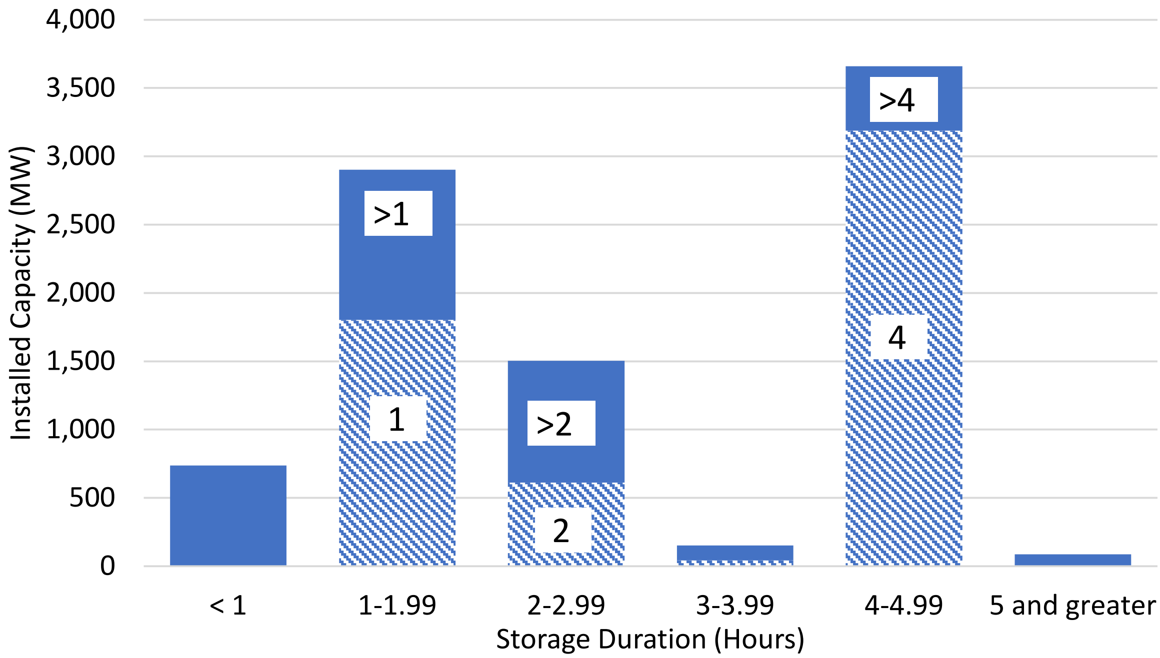

Figure 1. Distribution of energy storage durations for capacity completed during 2010–2022. Less than 7% of this capacity has duration greater than 4 hours.

Hatched bars indicate that the capacity has a duration of exactly 1, 2, 3, or 4 hours, as indicated.

A large fraction of capacity installed is exactly 4 hours, with 2,850 MW of 4-hour batteries installed in 2021 and 2022. Less than 7% of total capacity has a duration that exceeds 4 hours. This can be explained by examining how the benefits and costs of storage vary as a function of duration.

2.1 Framing the Storage Value Proposition

The value of storage is often tied to its ability to combine multiple services, or "value stacking."[8] Table 2 summarizes in broad categories some of the potential values of energy storage.

[8] This concept is not unique to storage, and many generation resources provide multiple service and thus inherently value-stack, although this term appears to be rarely used when talking about traditional generation capacity.

Table 2. Major Categories of Power System Storage Services

Service	Description
Capacity	Firm capacity and resource adequacy
Energy	Energy shifting/dispatch efficiency/avoided curtailment
Transmission	Avoided capacity, congestion relief
Ancillary Services/ Essential Reliability Services	Operating reserves, voltage support, and other services that provide operational reliability
Distribution	Avoided capacity, local reliability, and resilience

Note that Table 2 does not explicitly list renewable energy-specific applications, such as "renewable firming" or "renewable time-shifting." These applications are specific cases of the more general applications listed and are therefore already captured in Table 1. Likewise, Table 1 captures some applications that can be provided by behind-the-meter storage. For example, firm capacity and energy shifting value is reflected in some tariffs by demand charges and time-of-use rates.

Much of the deployment of storage between 2010–2019 focused on ancillary services (and particularly regulating reserves), served by batteries (and a few flywheels) often with 1 hour or less. The amount of storage now deployed in some regions exceeds the local regulating reserve requirements, and the amount of battery storage listed in Table 1 now exceeds the entire regulating reserve requirements in the United States of about 9 GW.[9] Furthermore, Table 1 does not include other resources that provide regulating reserves and reduce opportunities for new storage, including existing PSH and demand response.[10] As a result, regulating reserve markets (and other reserve markets) have the potential to saturate[11], and the focus of new storage deployments have shifted to capacity, as indicated by the jump in duration in 2022 and discussed in the next section.

2.2 The Value of Peaking Capacity and Implications of the 4-Hour Rule

Peaking capacity is used to meet demand on hot summer days, or in some locations, in periods of extreme cold, when the demand is well above average levels. Peaking capacity is typically provided by simple-cycle gas turbines, older gas steam plants, or internal-combustion generators, and there is about 260 GW of peaking capacity in the United States.[12] These technologies are chosen due to their low capital costs, with fuel and other variable costs being less important due

[9] The existing storage is not distributed regionally in proportion to regulation requirements. Discussion of total reserve requirements is provided in P. L. Denholm, Y. Sun, T. T. Mai. (2019). "An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind." https:/doi.org/10.2172/1505934.
[10] Anwar, M.B., M. Muratori, P. Jadun, E. Hale, B. Bush, P. Denholm, O. Ma, K. Podkaminer. (2022). "Assessing the value of electric vehicle managed charging: a review of methodologies and results." *Energy & Environmental Science* 15, 466-498.
[11] Additional solar and wind deployment can increase the amount of operating reserve requirements, but this increase is generally associated with flexibility/ramping reserves that are less valuable than regulating reserves.
[12] "EIA electric power annual." https://www.eia.gov/electricity/annual/.

to the low usage. As these plants are retired and demand during winter and summer peaks increases, new peaking capacity is continually needed. The continued decline in the costs of Li-ion batteries has increased their competitiveness over traditional sources.[13]

A storage plant providing peaking capacity provides two primary sources of value: the value of providing physical capacity, and the value of energy time-shifting.

The ability of a storage resource to serve as a capacity resource is reflected its capacity credit, which refers the fraction of the resources' installed capacity that could reliably be used to meet peak demand,[14] which is typically measured as a value (e.g., kilowatts) or a percentage of nameplate rating.[15]

In most regions of the United States, determination of both the need for new capacity and the capacity credit applied to new resources is established by some combination of state and market regulators, as well as the local market operator (in regions with wholesale markets). Several regions, including CAISO[16], MISO, NYISO, and SPP have established 4 hours as the minimum duration required to receive full capacity credit, while ISO-NE requires 2 hours.[17] The duration requirements are used for planning and procurement purposes by state regulators, ISOs and load-serving entities and for determining eligibility for compensation in capacity markets or under resource adequacy capacity contracts.[18]

In locations with a fixed duration requirement for capacity (such as the 4-hour capacity rule), storage plants receive full value at or above the duration requirement established by the market operator or regulator. A battery with less than the duration requirement can receive partial capacity value, as shown in Figure 2, representing a linear derate, so a 2-hour battery would receive half the credit of a 4-hour battery, but a 6-hour battery receives no more value or revenue (for providing capacity) than a 4-hour battery in this example.

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[13] Augustine, Chad, Nate Blair. (2021). *Storage Futures Study: Storage Technology Modeling Input Data Report*. NREL/TP-5700-78694.

[14] F. D. Munoz, A. D. Mills. (2015). "Endogenous Assessment of the Capacity Value of Solar PV in Generation Investment Planning Studies." *IEEE Transactions on Sustainable Energy* **6**, 1574–1585.

[15] The terms capacity credit and capacity value are often used interchangeably, although it has been suggested that capacity credit be used to represent physical capacity, and capacity value be used to represent the monetary value of this capacity (A. D. Mills, R. H. Wiser, "Changes in the economic value of photovoltaic generation at high penetration levels: A pilot case study of California" in 2012 IEEE 38th Photovoltaic Specialists Conference (PVSC) PART 2, (2012), pp. 1–9.).

[16] The requirement in the CAISO region is established by the California Public Utilities Commission (https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/electric-power-procurement/resource-adequacy-homepage).

[17] Denholm, P., W.J. Cole, A.W. Frazier, K. Podkaminer, N. Blair (2021) The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System. NREL/TP-6A20-77480.

[18] Several regions without restructured wholesale markets including Arizona and Nevada have installed batteries with exactly four hours of duration for the primary purpose of providing peaking capacity. https://www.sandia.gov/app/uploads/sites/163/2021/09/GESDB_ArizonaStorageSummary-1.pdf
https://www.sandia.gov/app/uploads/sites/163/2022/04/GESDB_Nevada_StorageSummary.pdf

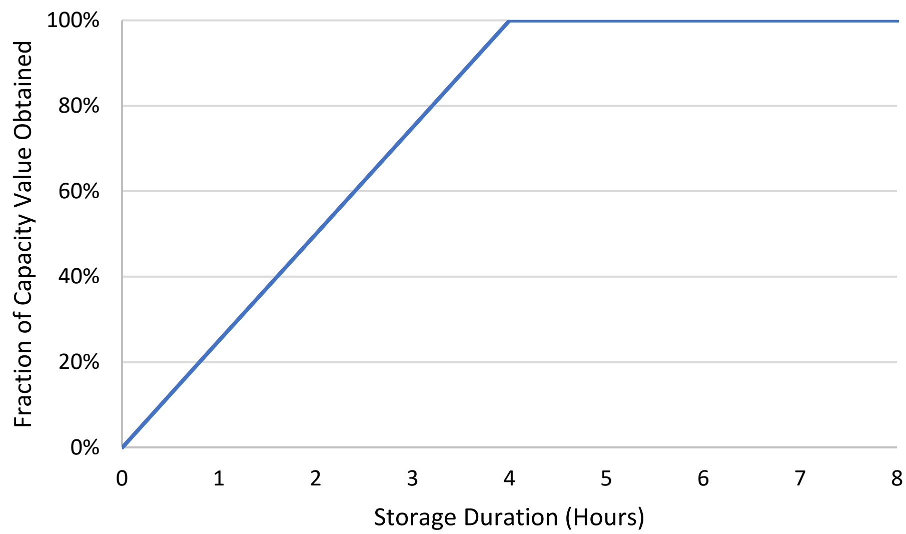

Figure 2. Fraction of capacity value captured as a function of duration for locations with the 4-hour capacity rule. Durations beyond 4 hours provides no additional financial value for provision of firm capacity.

An important secondary source of value for energy storage acting as a capacity resource is energy time-shifting/arbitrage, which in a market region is the value of storing low-cost off-peak energy and selling this stored energy during periods of higher prices. A battery peaking plant can provide both capacity and energy-shifting services simultaneously because the periods of highest prices (when the battery will discharge to maximize revenue or minimize system costs) are very highly correlated to periods of highest demand when the system needs reliable capacity.[19] Periods of low prices (when the battery will charge) are also periods of low demand, and therefore when large amounts of spare capacity are available and the risk of an outage is low. Therefore, these two services—capacity and time-shifting—can be "stacked" without double-counting.

Studies of the value of energy storage providing time-shifting demonstrate that much of the potential value can be captured with relatively short duration storage. Figure 3 shows an example of the fraction of potential value derived from a storage device as a function of duration, compared to a 40-hour device.[20] In this example, storage revenue was simulated in several market regions using several years of recent historical prices. While the absolute value varies considerably depending on location and factors such as transmission constraints, the general trend in value as a function of duration is similar. The first hour of storage has the highest value, as it is arbitraging the largest spread in market prices. Each subsequent hour is arbitraging a much smaller price difference. The curve in orange shows a region where a 4-hour battery receives the highest fraction of the theoretical potential and therefore "best" for 4-hour storage.

[19] R. Sioshansi, S. H. Madaeni, P. Denholm. (2014). "A Dynamic Programming Approach to Estimate the Capacity Value of Energy Storage." *IEEE Transactions on Power Systems* 29, 395–403.

[20] Analysis uses a price-taker model using a round trip efficiency of 85% for one year of hourly data. We only show results up to 40 hours, as at that point the incremental value for additional hours of duration was increasing by less than 0.001%. Emmanuel, M.I., P. Denholm. (2022). "A market feedback framework for improved estimates of the arbitrage value of energy storage using price-taker models." *Applied Energy*. 310:118250.

The curve in blue shows results for a region where longer durations are required to receive greater revenue; however, even in this region, a 4-hour device captured more than 60% of the value that could be obtained by a 40-hour device. Also of note is that it is unlikely that the 40-hour device would be able to receive its full potential, as this would require optimization of the storage device over a multiweek operational horizon with perfect foresight.[21]

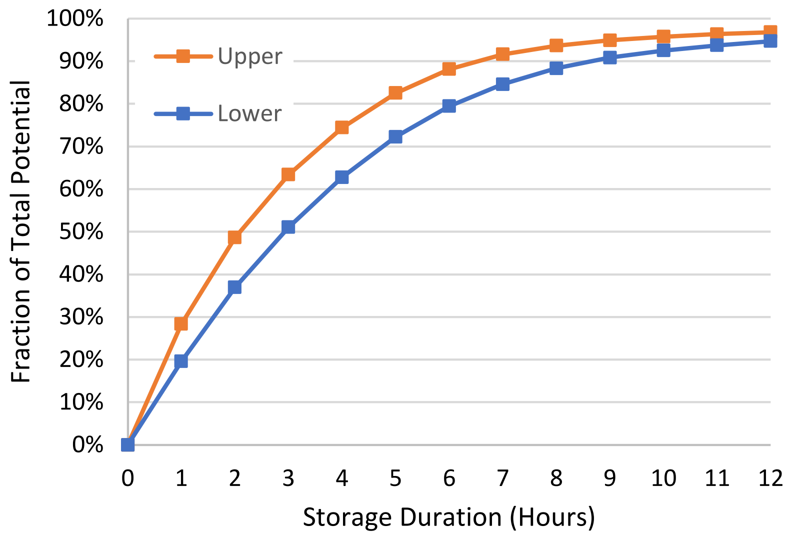

Figure 3. The first few hours of a storage device provide the majority of the time-shifting value, with a 4-hour device capturing more than 60% of the value obtained by a 40-hour storage device.

Results are derived from historical market regions, and the two curves shown represent an upper and lower bound for the fraction of revenue captured by devices of different durations.

Using estimates for the value of capacity and energy time-shifting, Figure 4 (top) provides an estimated range of the annualized value of the combination of capacity and energy time-shifting ($/kW-yr) as a function of duration. The value for capacity uses the linear relationship between duration and value, assuming a 4-hour capacity rule and using two values for capacity: a lower value of $80/kW-yr and higher value of $150/kW-yr.[22] This is combined with the value of energy time-shifting curve from Figure 3, using a lower value of $60/kW-yr and a higher value $120/kW-yr.[23] [24] The fraction of potential value shown at 4 hours (84% to 88%) is relative to the

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[21] This implies that the 4-hour device, with its shorter optimization window, would actually likely receive an even higher fraction of its total potential.

[22] In real systems, determination of long-term capacity and energy prices is very complicated, given the evolving generation mix, actual need for new capacity, and market rules that limit scarcity prices that may occur during periods of peak demand (J. Bistline et al. (2020). "Energy storage in long-term system models: a review of considerations, best practices, and research needs." *Progress in Energy* 2, 032001. 29). In locations with sufficient capacity, the value of additional capacity can be very low, as reflected in low capacity prices in markets that approach or exceed reliability planning standards.

[23] Prices for capacity are often measured in units of capacity available for 1 hour (MW-hr). Some regions use cost per kW-month. This is also similar to how payments in capacity markets may be measured in kW-yr, or the provision of 1 kW of capacity for a 1-year period.

[24] $90/kW-yr. This value is roughly equal to the estimated net cost of a new entrant for a peaking combustion turbine in MISO and PJM in 2020 (PJM. (2020). "Default MOPR Floor Offer Prices for New Generation Capacity

longer-duration device, so it represents the weighted average of value of capacity (100% at 4 hours) and time-shifting (about 62% to 75%).

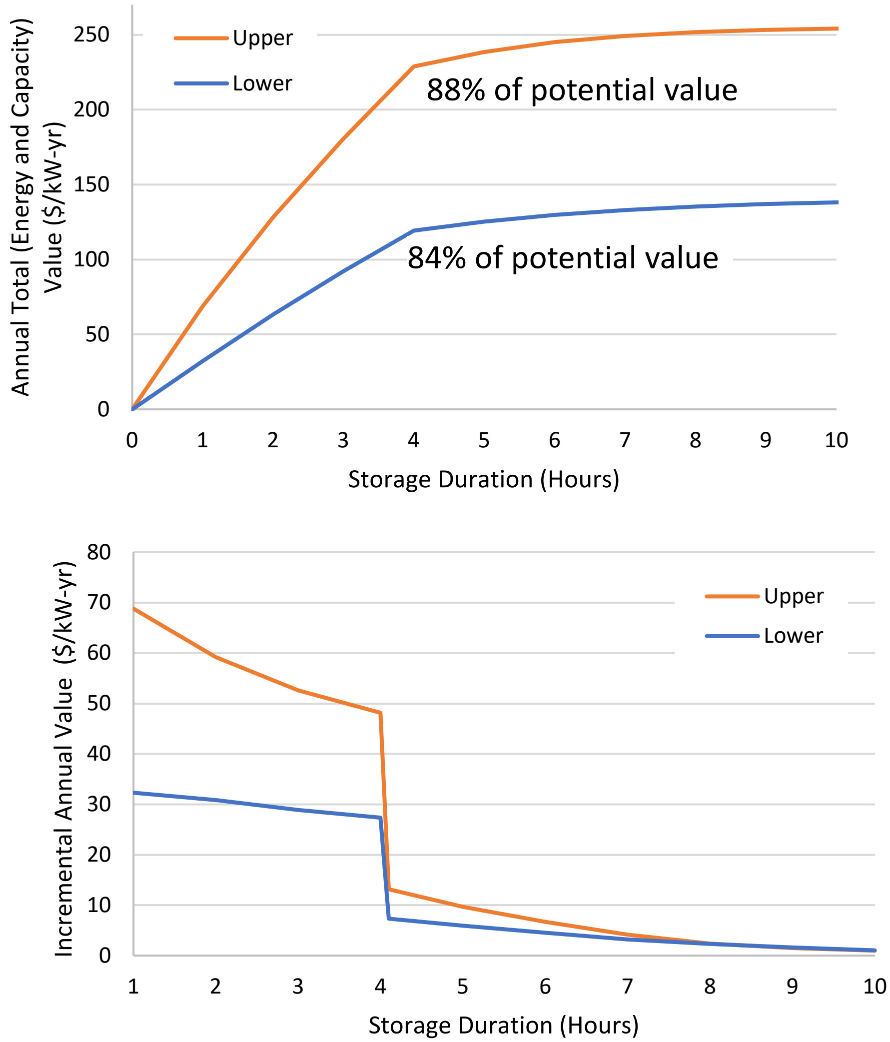

Figure 4. In locations with a 4-hour capacity rule, a 4-hour storage device captures well over 80% of the total capacity plus energy time-shifting value that could be captured by a much longer device (top). The incremental value of adding additional duration (bottom) is less than the annualized cost of current Li-ion battery capacity.

The combination of the 4-hour capacity rule and the shape of the arbitrage value curve result in little economic incentive for deploying durations beyond 4 hours in many locations. This is demonstrated by examining the incremental value, or the annualized value of an extra kWh of storage, shown in Figure 4 (bottom). Because of the 4-hour rule for capacity, any incremental value beyond 4 hours is limited to the relatively small residual value of energy time-shifting. The

Resources." MISO. (2019). "Cost of New Entry PY 2020/21." It is important to note that this value is higher than many historical capacity prices that occurred during periods when systems had sufficient capacity to meet the local requirements.

value for a fifth hour of storage (using historical market data) is less than most estimates for the annualized cost of adding Li-ion battery capacity, at least at current costs.[25] As a result, moving beyond 4-hour Li-ion will likely require a change in both the value proposition and storage costs, discussed in the following sections.

[25] For example, applying a fixed charge rate of 9%, an annual value of $10/kW-yr would require a capital cost of about $110/kWh, which is below most estimates for the cost of Li-ion battery modules (Cole, Wesley; Karmakar, Akash. (2023). *Cost Projections for Utility-Scale Battery Storage: 2023 Update*. NREL/TP-6A40-85332).

3 Moving Beyond 4 Hours: Shifting the Value Proposition

We describe two general changes that may shift the value proposition to storage with greater than 4 hours, illustrated conceptually in Figure 5. The changes are illustrated relative to the value proposition for storage in a current system with a 4-hour capacity rule described in Section 2 (orange line). The first potential shift (illustrated in the gray line) is a shift in the value of existing services toward longer duration, as discussed in Section 3.1. The second potential change (illustrated in the blue line) is the provision of new sources of value that favor longer durations. These are discussed in Section 3.2. It is important to note that we are considering changes that will occur in the relatively near term, as opposed to changes that will occur associated with extremely large-scale deployment of renewables and deep decarbonization.

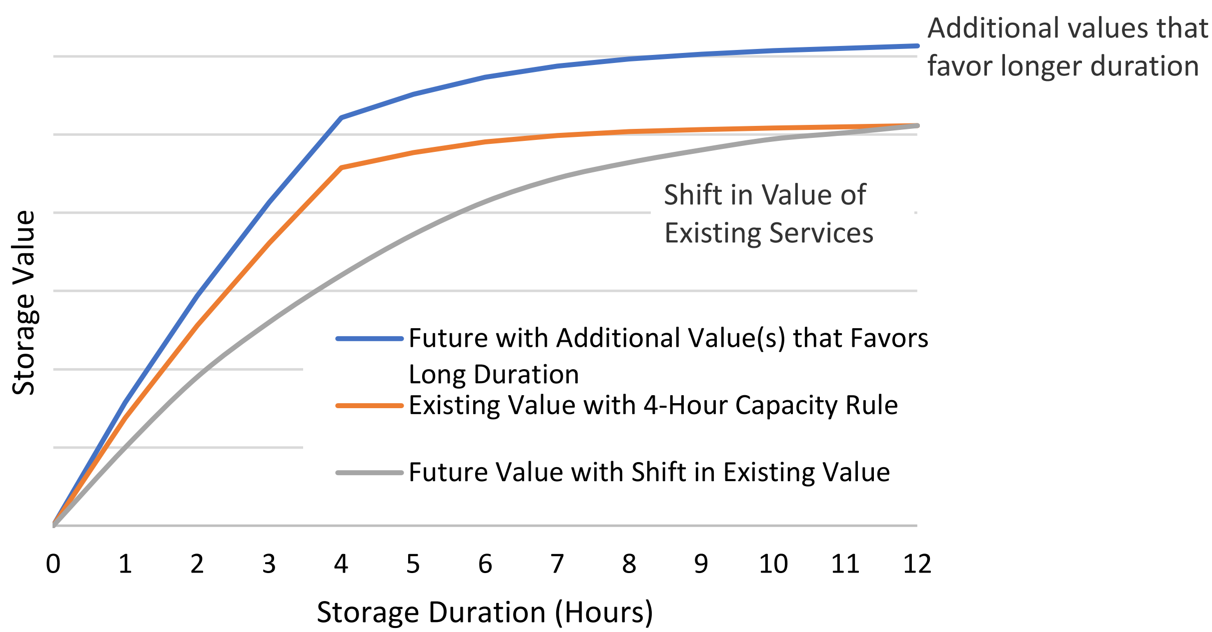

Figure 5. Two changes that could shift in the value proposition toward longer-duration energy storage include a shift in value of existing services (primarily a reduction in the value of shorter-duration storage) and provision of additional services that are suited for longer duration.

3.1 Beyond the 4-Hour Rule: Shifting the Capacity Value Curve

The 4-hour capacity rule is a simplification of a more complicated relationship between capacity value and duration, and it reflects near-term conditions (and only in some regions). Over time, rules will likely evolve to reflect changes in grid conditions that could shift the shape of the value curve and potentially incentivize longer-duration storage.

Accounting for Nonlinear Derates and ELCC-Based Capacity Value

The 4-hour rule and the linear derate curve shown in Figure 2 is based on the existing rules for obtaining capacity value in various markets. While 4 hours has been demonstrated to provide significant capacity credit, the linear derate curve is a simplification of a more complicated relationship between duration and capacity, driven in part by uncertainty of load shapes and the ability to forecast weather. A more sophisticated approach to evaluating the capacity credit of storage uses effective load carrying capability (ELCC), and accounts for the probabilistic nature of power system operation.[26] Figure 6 shows ELCC estimates used by PJM for their 2024 capacity accreditation, and Idaho Power in their 2023 integrated resource plan.[27] In this figure, we show only points provided by the reference, and the lines are simple interpolations, which does not reflect the potential change in shape associated with durations of less than 4 hours. This follows other ELCC analysis that shows capacity credit of storage having a steeper initial slope at shorter durations, tapering off with a long "tail."[28]

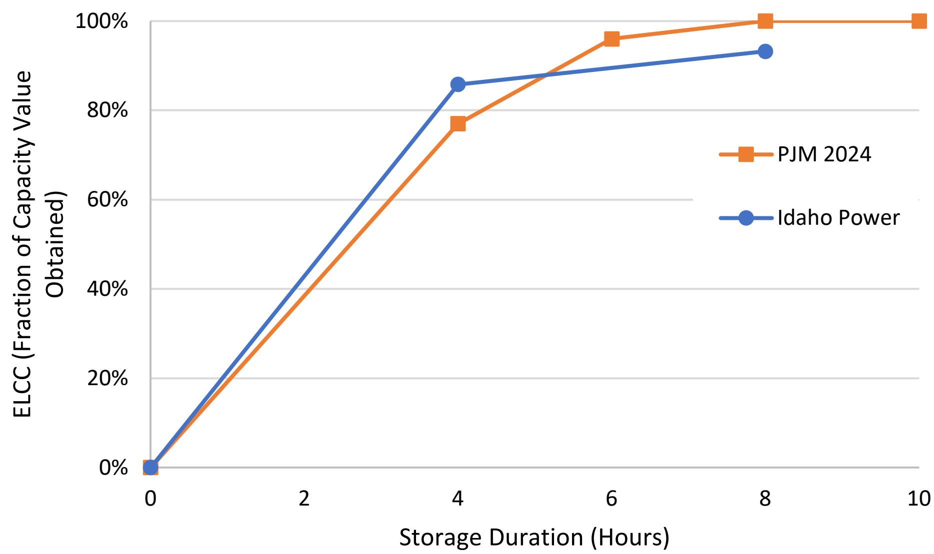

Figure 6. Annualized capacity value as a function of duration in PJM and Idaho Power using ELCC shows the potential for additional value beyond 4 hours.

Other regions have historically used ELCC approaches for evaluating solar and wind, and are now transitioning to more sophisticated ELCC approaches for storage as well, recognizing the limits of simple linear derates.[29] It is important to note that the use of nonlinear derate curves and ELCC methods does not increase the absolute value of longer durations—its impact on value is to (potentially) decrease the value of 4-hour storage, which can make longer durations more competitive.

While the use of ELCC values could help shift opportunities, the effect is somewhat limited. Even using an ELCC approach, the capacity value of 4-hour storage in summer-peaking systems

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[26] Specht, Mark. (2021). "To Understand Energy Storage, You Must Understand ELCC." *The Equation.* https://blog.ucsusa.org/mark-specht/to-understand-energy-storage-you-must-understand-elcc/.
[27] Valdepana Delgado, Andres, Shelby McNeilly. "Reliability &Capacity Assessment Update." Idaho Power. https://docs.idahopower.com/pdfs/AboutUs/PlanningForFuture/irp/2023/2023_03_07_PRM_ELCC_WRAP.pdf.
[28] R. Sioshansi, S. H. Madaeni, P. Denholm. (2014). "A Dynamic Programming Approach to Estimate the Capacity Value of Energy Storage." *IEEE Transactions on Power Systems* 29, 395–403.
[29] https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M389/K603/389603637.PDF and https://cdn.misoenergy.org/2022%20Wind%20and%20Solar%20Capacity%20Credit%20Report618340.pdf

can be very close to 100%[30]; a far greater impact will be the change in net load shape due to changes in grid mix.

The Shift to Longer Net Load Peaks, Particularly in the Winter

Even without sophisticated analysis, the basis for the 4-hour rule can be observed by examining the shapes of normal summer peak demand patterns that are typically well under 4 hours long in much of the United States. However, the shape and length of the peak demand period is changing due to an evolving grid mix, load, and weather patterns, with confounding factors that will both increase and decrease the value of 4-hour storage, ultimately impacting the value proposition for longer-duration storage.[31]

Figure 7 illustrates the two primary factors that affect the value of 4-hour storage to provide peaking capacity. First, as more 4-hour storage is deployed (without any other changes to the grid mix), the incremental capacity credit of this storage declines. Figure 7a illustrates this concept in a simulated scenario in which California deploys about 4,500 MW of 4-hour storage, or enough to meet about 8% of annual peak demand using 2013 load and weather patterns.[32] At this point, storage has clipped the peak, and the remaining peak period (net peak) is about 6 hours long. This shows how, as more energy storage is deployed, the peaks become wider and energy storage is less able to meet the resulting longer periods of peak demand. This means planners would need to reduce the capacity credit for additional storage. In this example, if the 4-hour rule were adjusted accordingly (becoming a “6-hour” rule), a 4-hour device would need to be derated by one-third. However, this decline in value will be offset to varying degrees by the deployment of solar PV, which tends to narrow the net load peak, as illustrated in Figure 7b. This example subtracts simulated PV output from normal load on the same peak day as the top figure, with annual PV contributions from 0% to 20%.

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30 Carden, Kevin, Alex Dombrowsky, Rajaz Amitava. (2022). *Effective Load Carrying Capability Study.* https://www.astrape.com/wp-content/uploads/2023/01/2022-ERCOT-ELCC-Study-Final-Report-12-9-2022.pdf.

31 In this section, we focus on how net load shapes will impact the capacity value of storage. Changing net load shapes will also impact the energy arbitrage value of storage. Like with the capacity value, the energy arbitrage opportunity can grow or shrink based on the specifics of the generation mix and load shape in a particular region.

32 P. Denholm, J. Nunemaker, P. Gagnon, W. Cole. (2019). *The potential for battery energy storage to provide peaking capacity in the United States. Renewable Energy.* https:/doi.org/10.1016/j.renene.2019.11.117.

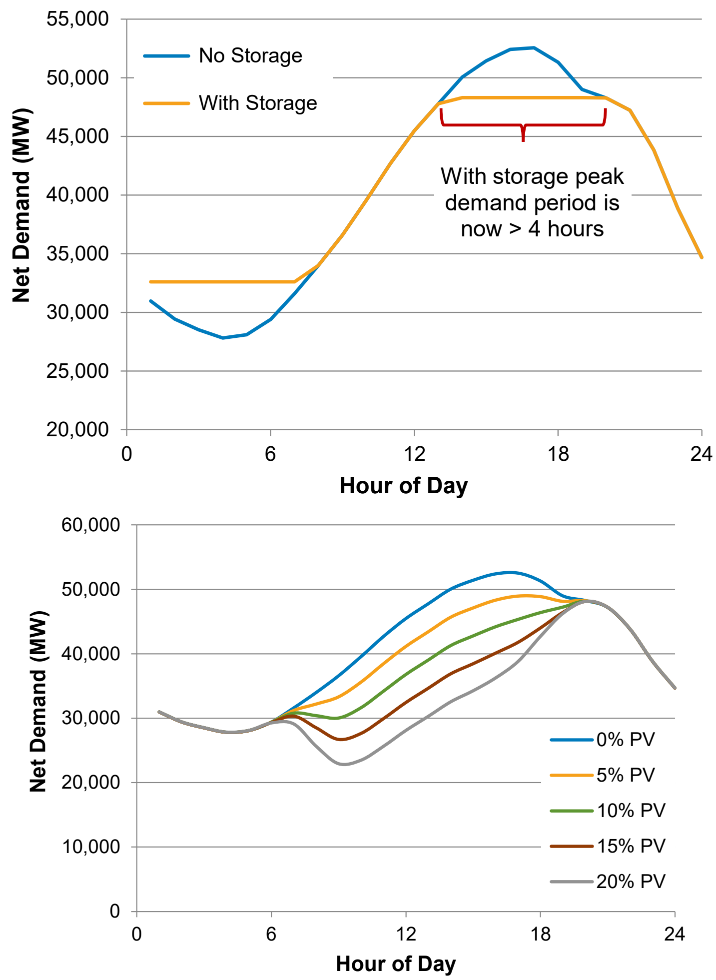


Figure 7. Simulated impact of increased 4-hour storage deployment on net load shape in California (top) demonstrates how storage can reduce the net load peak, but also make it longer. This increase in net peak length can be offset by added solar (bottom) and delay the decline in capacity value of additional storage.

The potential for 4-hour storage to address peak demand in strongly summer-peaking systems has been demonstrated in several studies, and also by real-world events. Figure 8 shows the demand (blue) and net demand with PV and wind (red) during August 14 and 15, 2020, in California,[33] where extremely high temperatures, along with several other factors, led to rotating electricity outages.[34] The outages lasted 2.5 hours on the 14th, and 1.5 hours on 15th. Storage with 4 hours of duration (or less) with sufficient power capacity could have provided enough energy to avoid these outages, especially because of the low net demand period in the morning, which would have provided sufficient opportunity to recharge.

[33] Data is from the CAISO portion of the California grid, which is about 85% of the state's demand.
[34] CAISO. (2021). *Root Cause Analysis.* http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf.

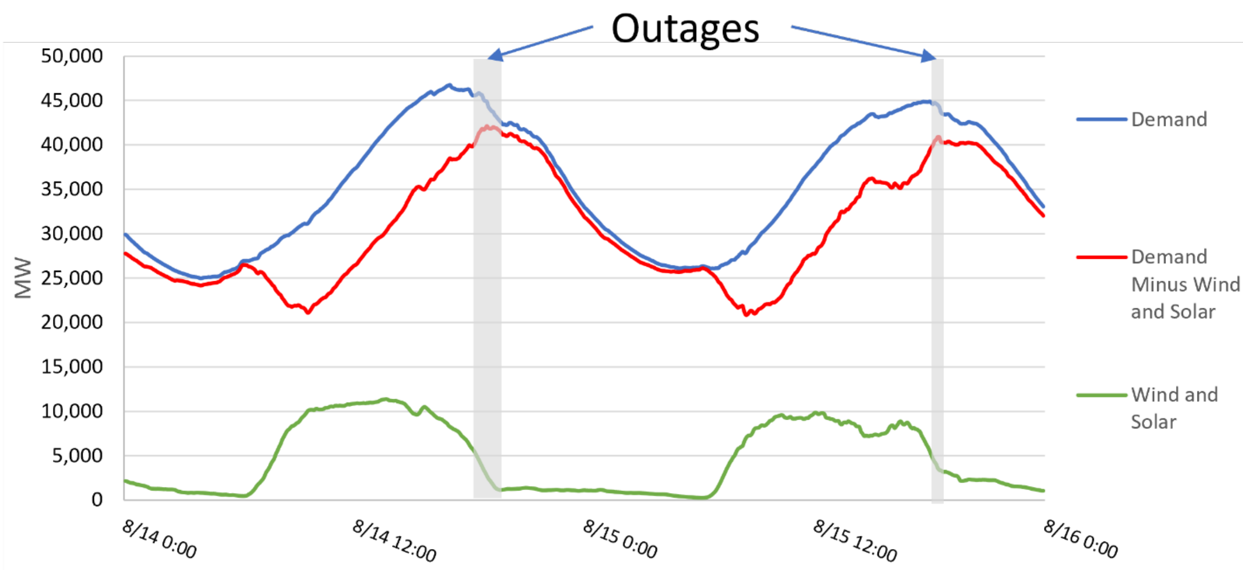


Figure 8. The California 2020 resource adequacy event resulted in rolling blackouts for as long as 2.5 hours (gray bars). 4-hour storage with sufficient power capacity would have been sufficient to avoid this event, with the ability to recharge overnight during off-peak periods.

The ability of PV to delay the decline in value of 4-hour storage is greatest in strongly summer-peaking systems such as in California and the Southwest, but has been demonstrated in other locations. Figure 9 shows the results from a study of the ELCC of 4-hour storage in PJM.[35] The change over time is due to the assumed change in grid mix, including growth in solar deployment. This addition results in the continual decline in PV ELCC (orange) as net load peaks are shifted, but an increase in 4-hour storage ELCC over time (blue) due to this narrowing peak, actually reaching close to 100% by 2030.

[35] PJM. December 2022 Effective Load Carrying Capability (ELCC) Report.

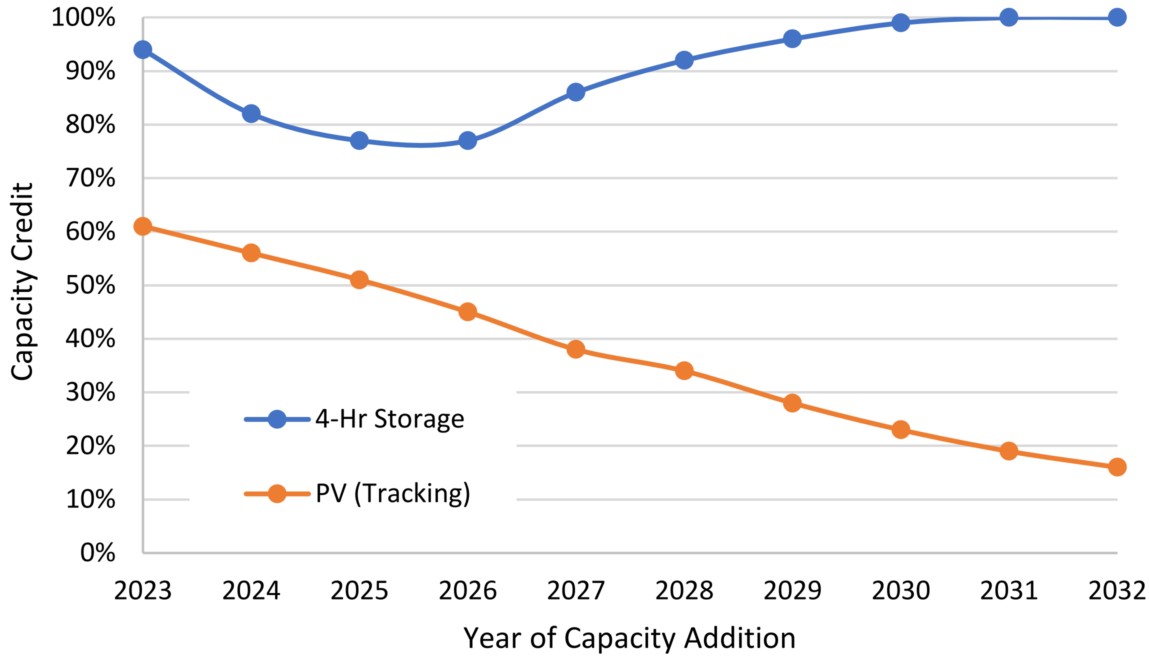


Figure 9. Deployment of PV in the PJM region over time reduces its ELCC, while substantially increasing the ELCC of 4-hour storage, maintaining its ability to provide firm capacity.

As a result, the more near-term opportunity for longer-duration storage will occur due to a shift in demand peaks to winter. Resource adequacy metrics such as ELCC identify the periods of greatest likelihood of a shortfall in meeting demand, and ELCC metrics are dominated by summer peaks in much of today's grid.[36] However, a shift of (net) peak demand periods to the winter means ELCC will be more likely to be measured by winter performance.

Net winter peaks can result from the large supply of solar decreasing the summer peak, while making less significant contribution during the winter.[37] Figure 10 compares the winter and summer peak profiles for ERCOT in 2022. The solid line shows the normal demand profile, where the summer peak (occurring July 20) was about 8% higher than the winter peak (December 23). However, the dashed lines show the net peak with solar, where significant solar production produced a net winter peak overall.

[36] A. W. Frazier, W. Cole, P. Denholm, D. Greer, P. Gagnon. (2020). "Assessing the potential of battery storage as a peaking capacity resource in the United States." *Applied Energy* 275, 115385.
[37] Cole, Wesley, Paul Denholm, Vincent Carag, Will Frazier. (2023). "The Peaking Potential of Long-Duration Energy Storage in the United States Power System." *Journal of Energy Storage* 62.

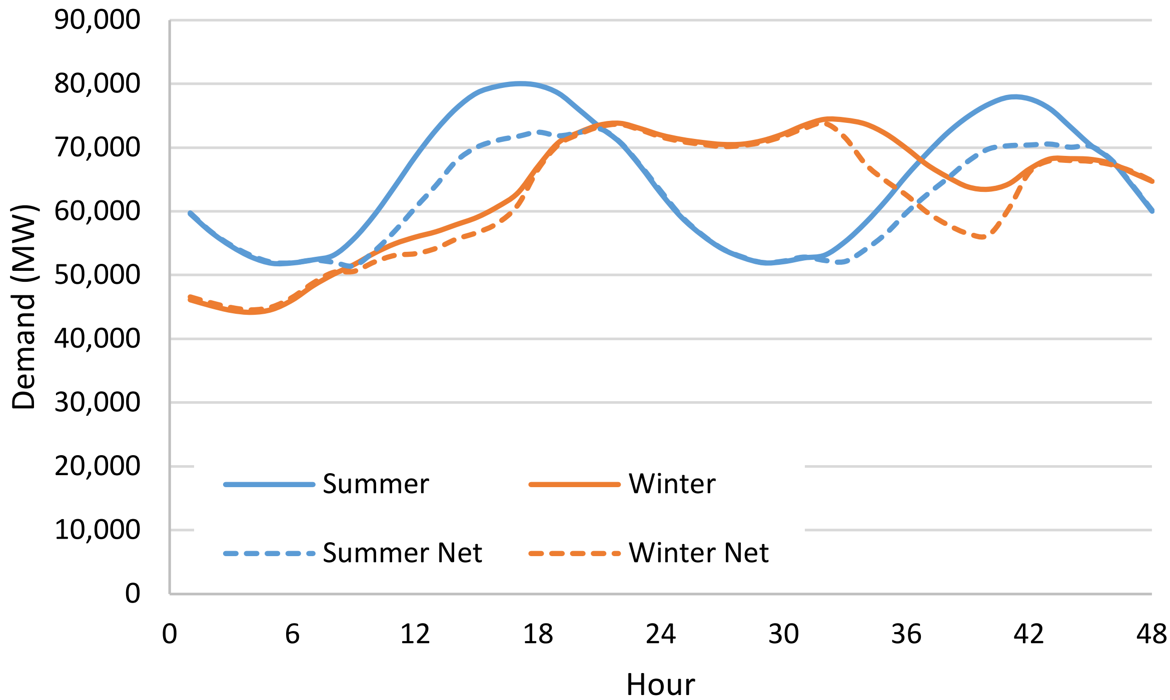
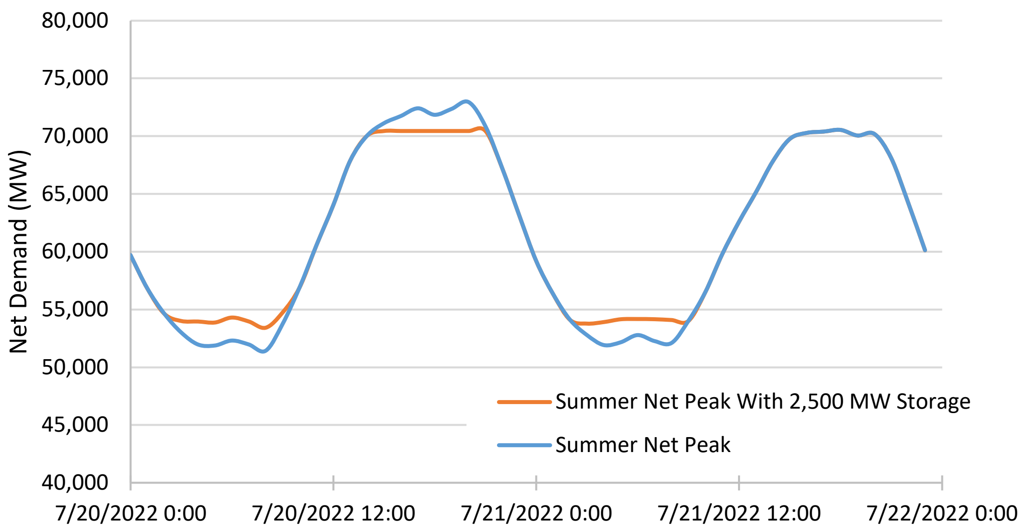


Figure 10. Comparison of winter and summer peak shapes in ERCOT in 2022 shows a transition to net winter peaks, with the impact of solar on summer peaks and winter peaks being flatter and longer.

The shift to winter peaks (either net winter peaks due increased use of solar, or actual winter peaks due to increases in winter electric demand) is important because winter peaks tend to be longer than summer peaks, which reduces the ability of shorter-duration storage to have high capacity credit. This is illustrated in Figure 11, which simulates the impact of storage on net load shapes using the 2022 ERCOT data. The top chart (July 20–21) shows the impact of storage on the summer peak net load, and while the peak has widened, it is still about 4 to 5 hours long, which means 4-hour storage would retain close to full capacity credit. However, the bottom chart (December 22–23) shows how the net peak in the winter has widened to about 8 hours long, as there is little opportunity to recharge in the overnight period where demand is still very high.



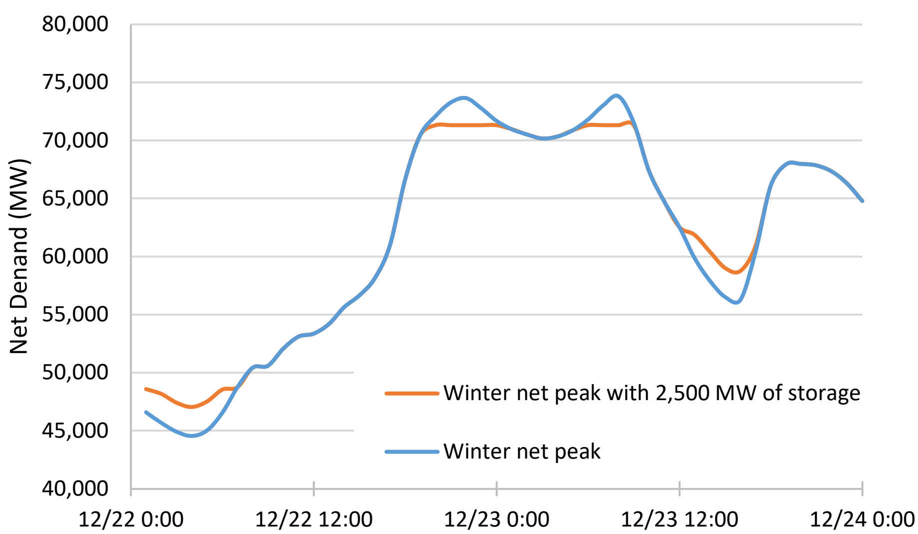


Figure 11. Addition of 2,500 MW of simulated storage in ERCOT widens net load peaks in the summer (top), but the wider peaks can be offset by additional solar. The impact of storage in the winter (bottom) is to widen the net peak mostly at night, which cannot be reduced with solar. This would require significantly more than 4 hours of duration to provide high capacity credit.

Figure 12 shows the decline in ELCC of 4-hour storage in ERCOT using a more comprehensive ELCC analysis.[38] The x-axis shows the total amount of wind, solar, and storage deployed, assuming no other changes in load. The y-axis shows the incremental capacity credit of additional 4-hour storage either in the summer (blue) or winter (red). The summer curve follows other examples where the capacity credit first drops as more storage is deployed, and then increases as solar acts to narrow the net load peak. However, the winter capacity credit drops

[38] Carden, Kevin, Alex Dombrowsky, Rajaz Amitava. (2022). *Effective Load Carrying Capability Study.* https://www.astrape.com/wp-content/uploads/2023/01/2022-ERCOT-ELCC-Study-Final-Report-12-9-2022.pdf.

fairly rapidly, and by the time storage is serving about 3%–4% of net peak demand, the value of an incremental 4-hour device is about 75%, meaning it has lost about 25% of its capacity value.

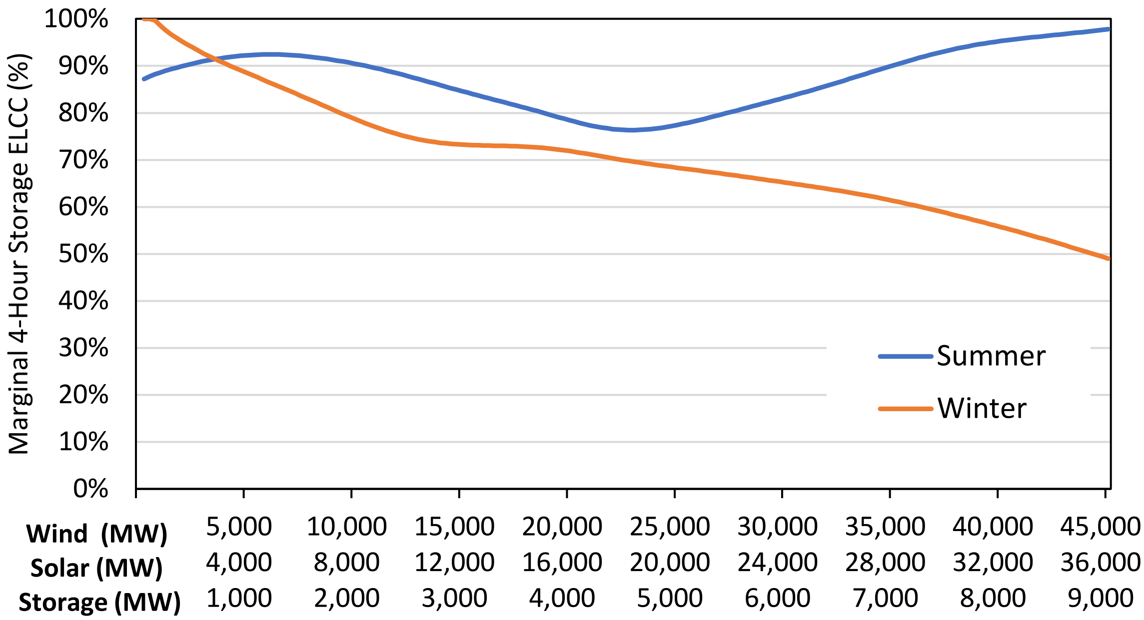


Figure 12. The capacity credit of 4-hour storage in the summer in ERCOT is maintained or increased as PV is deployed, but the capacity credit of 4-hour storage declines considerably as net load peaks are lengthened.

The x-axis shows the total amount of wind, solar, and storage deployed. For example, the points on the right-most portion of the graph are for a system with 45,000 MW of wind, 36,000 MW of solar, *and* 9,000 MW of storage.[39]

A few regions of the United States are already winter peaking, or are close to winter peaking even before the addition of solar. These are typically regions with fairly mild climates that rely on electric heating; Figure 13 shows the ratio of summer to winter peak from the North American Electric Reliability Corporation's 2022 summer and 2022/2023 winter reliability assessment reports.[40] [41] In addition to the Northwest, several regions in the Southeast are now considered winter peaking, particularly regions with historically mild winters that rely on a greater fraction of electric heating. Texas is considered winter peaking in extreme weather conditions, but as already demonstrated in the ERCOT example, deployments of solar have already resulted in a shift to net winter peak, at least in 2022.

[39] Data provided by Astrape from https://www.astrape.com/wp-content/uploads/2023/01/2022-ERCOT-ELCC-Study-Final-Report-12-9-2022.pdf.
[40] NERC. (2022). "2022 Summer Reliability Assessment." https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_2022.pdf.
[41] NERC. (2022). "2022–2023 Winter Reliability Assessment." https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_WRA_2022.pdf.

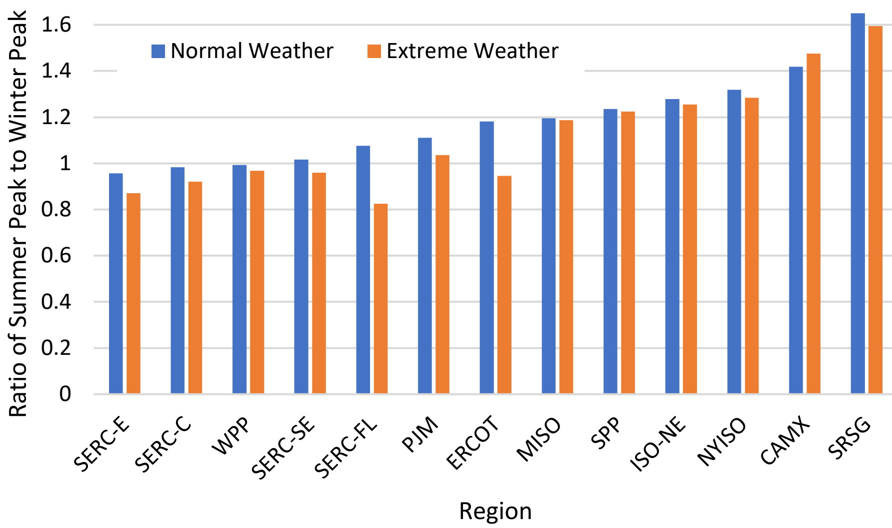


Figure 13. Ratio of summer to winter peak, where values less than 1 represent winter peaking systems. Large areas of the country, including the Southeast and Texas are now considered winter peaking during either normal or extreme weather conditions.

The more strongly summer-peaking systems are either places with warm climates (and where it does not get cold in the winter) or in locations that tend to have cold winters and therefore tend to rely on (historically) less costly fossil-fuels for heating. In the latter case, electrification could also lead to winter peaks, even without the impact of solar on summer peak demand reduction. Figure 14 illustrates results from a set of simulations that explores the possible change in load shape throughout the United States due to electrification.[42] The example is from the NYISO region and shows how the summer peak in 2020 is significantly greater than the winter peak, but the 2032 scenarios show a significant growth in winter peak. This increase in winter peak, combined with the greater contribution of PV, would result in a shift to a net winter peak.

[42] Denholm, P., P. Brown, W. Cole, et al. (2022). *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035*. Golden, CO: National Renewable Energy Laboratory. NREL/TP6A40-81644.

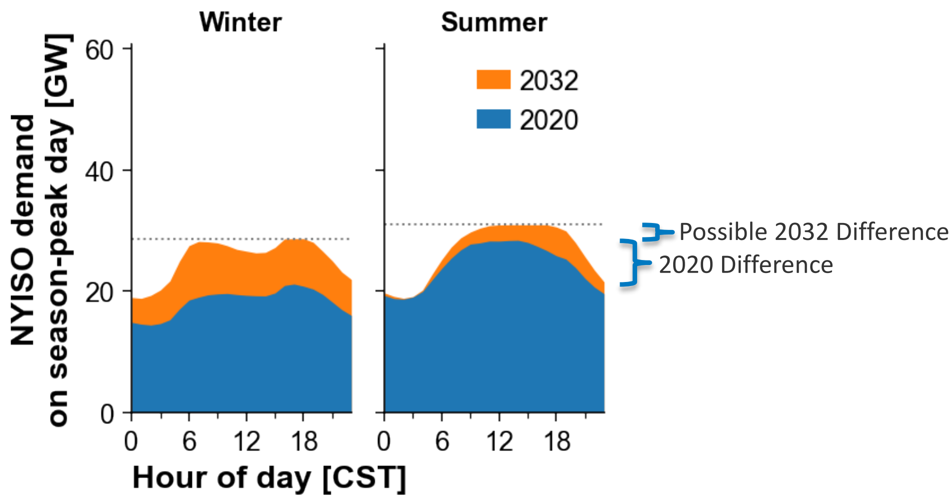


Figure 14. Example of the impact of electrification on the day with annual peak demand in NYISO, which could lead to a winter peak in the coming decade

Overall, while continued deployment of solar can maintain the ability of 4-hour storage to provide significant capacity during summer peaks, this solar deployment will also accelerate the shift to net winter peaks in much of the country. This then will likely drive the decline in capacity value of 4-hour storage and incentivize longer durations.

3.2 Additional Services Increasing the Value of Longer-Duration Storage

Four-hour storage is now economic for provision of capacity and energy services discussed in the previous section, but there are potentially other sources of value that could incentivize longer-duration storage. Additional services can potentially provide more value for longer-duration storage if those services can:

1. Avoid double-counting (meaning they interfere with the ability to provide services already accounted for).
2. Be monetizable in current market environments (or be valued by regulators under a rate-of-return framework).
3. Favor longer-duration storage.
4. Reflect the ability to site storage in locations where the services are available.

Not having these factors limits the ability of longer-duration storage to provide certain services. For example, there are new or emerging operating reserve products such as frequency response or a flexible ramping product that provide new revenue opportunities for storage (addressing Factor 2). However, the limited-duration requirements (well under 1 hour)[43] do not provide a strong incentive for longer-duration storage, so this application is ultimately limited by Factor 3. Another example is providing distribution services, where longer durations may be valuable, but

[43] Denholm, P.; Y. Sun; T. Mai. (2019). *An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind*. NREL/TP-6A20-72578.

Factor 4 may be a limit, as some longer-duration storage technologies have large physical footprints due to the need for deployment at scale and may have limited ability to be sited in the distribution network. Alternatively, we provide two examples of additional services that could be provided that (potentially) can meet these four criteria.

Transmission

One potential service that may favor longer duration is transmission investment deferral and congestion management. New transmission is added for many reasons, including improved reliability, relieving congestion and improving access to low-cost energy resources, and improving system stability.

In some cases, storage can act as a partial alternative to transmission upgrades.[44] An example is how storage can act to relieve transmission congestion. Congestion leads to higher prices in some regions that cannot access lower-cost resources behind the congested lines.[45] Storage can be placed on the "load" side of the congestion and charge during periods of lower congestion, then discharge during periods when the transmission is fully utilized.

This principal can also be applied to the use of storage to improve utilization of new transmission developed for remote variable renewable energy resources.[46] In this application, storage is placed on the "supply" side of the congested line. Some of the highest-quality wind resources in the United States are in more-remote locations that might require dedicated new long-distance lines to high-population load centers. Utilization of these transmission lines will be limited by the capacity factor of the wind resource (increasing costs per unit of delivered energy). Storage can be used to increase transmission utilization (increasing the amount of energy that can be delivered per unit of transmission capacity).[47]

The use of storage for transmission investment deferral is an example of an application that can be partially additive ("stacked") with system capacity and time-shifting, but careful analysis is required because this application inherently limits the flexibility of the storage device to charge and discharge independently of transmission constraints. In these applications, the sizing of the storage project is very specifically determined by the identified need and the composition of the portfolio of deferral solutions (which can include both supply, demand and transmission

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[44] Manocha, Aneesha, Neha Patankar, Jesse D. Jenkins. (2023). "Reducing transmission expansion by co-optimizing sizing of wind, solar, storage and grid connection capacity." *Applied Energy.* https://arxiv.org/pdf/2303.11586.pdf.
[45] Millstein, Dev, Wiser, Ryan H., Gorman, Will, Jeong, Seongeun, Kim, James Hyungkwan, and Ancell, Amos. (2022). *Empirical Estimates of Transmission Value using Locational Marginal Prices*. doi:10.2172/1879833.https://www.osti.gov/biblio/1879833.
[46] Manocha, Aneesha, Neha Patankar, Jesse D. Jenkins. (2023). "Reducing transmission expansion by co-optimizing sizing of wind, solar, storage and grid connection capacity." *Applied Energy.* https://arxiv.org/pdf/2303.11586.pdf.
[47] T. M. Jennie Jorgenson. (2020). "Reducing Wind Curtailment through Transmission Expansion in a Wind Vision Future."

solutions), although in general longer-duration storage provides even greater flexibility to avoid upgrades.[48,49]

Challenges of combining the value of transmission, capacity, and energy time-shifting include monetization, especially in regions with wholesale markets. The value of system capacity and energy time-shifting are largely monetizable in existing market structures via some combination of energy price arbitrage, capacity market payments, scarcity pricing, and bilateral capacity contracts. Some of the value of transmission deferral in market regions can be captured via congestion-related prices. However, not all of the value of storage used for transmission services may be captured in existing market products, and the addition of storage to relieve congestion may inherently reduce congestion prices, reducing the economic incentive for storage to be deployed for this purpose. There are opportunities for storage to be deployed as a transmission asset based on a rate-of-return mechanism,[50] however this precludes provision of additional market services, limiting the value of storage's flexibility. This has been noted previously, and there are ongoing efforts to address these challenges.[51] In vertically integrated systems, capturing this transmission value might be more straightforward.[52]

Resilience and Backup Power

Another example of an additional potential service served by longer-duration storage is resilience and backup power during extended outages. Because longer-duration systems can store more energy, they have the potential to be more valuable than shorter-duration storage when unplanned or extreme events disrupt the system.[53] Monetizing this value can be challenging, as resilience is not currently an established market product. However, bilateral contracts, changes to tariff rates, or other custom arrangements can provide a means to monetize benefits for provision of backup power to utilities, regional microgrids, or in behind-the-meter applications for large commercial and industrial customers.[54] As with transmission services, it may be possible to somewhat easier to deploy storage for this service in regions that allow for rate-based deployments (assuming the value can be justified to regulatory agencies). Behind-the-meter applications could potentially combine the value of backup service with avoided capacity and

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[48] T. M. Jennie Jorgenson, Reducing Wind Curtailment through Transmission Expansion in a Wind Vision Future (2017) https://doi.org/10.2172/1339078 .
[49] Jeremiah X. Johnson, Robert De Kleine, Gregory A. Keoleian, Assessment of energy storage for transmission-constrained wind, Applied Energy, Volume 124, 2014, Pages 377-388, ISSN 0306-2619
[50] https://www.nyiso.com/documents/20142/38699263/Storage%20as%20Transmission%20-%20Introduction.pdf/c5458a07-4be6-fe57-bef6-514abdcb725c
[51] Singer, Stephen. (2023). "Generators, transmission utilities, other back ISO-NE storage-as-transmission plan, with conditions." *UtilityDive.* https://www.utilitydive.com/news/iso-new-england-storage-as-transmission-ferc-union-concerned-scientists/640913/. *Inside Energy.* (2020). "Electric Storage May Be Treated As Transmission." https://www.insideenergyandenvironment.com/2020/08/electric-storage-may-be-treated-as-transmission/.
[52] JB Twitchell, JD Taft, R O'Neil, A Becker-Dippmann Regulatory Implications of Embedded Grid Energy Storage April 2021 https://energystorage.pnnl.gov/pdf/PNNL-30172.pdf
[53] Paul Albertus, Joseph S. Manser, Scott Litzelman, Long-Duration Electricity Storage Applications, Economics, and Technologies, Joule, 4:1,2020, Pages 21-32, ISSN 2542-4351, https://doi.org/10.1016/j.joule.2019.11.009
[54] Prasanna, Ashreeta, Kevin McCabe, Benjamin Sigrin, Nate Blair. *Storage Futures Study: Distributed Solar and Storage Outlook: Methodology and Scenarios.* NREL/TP-7A40-79790

energy time-shifting value captured in rate structures (via demand charges or time-of-use rates).[55] As with other services, careful analysis is required to avoid double-counting.

[55] N. D. Laws, K. Anderson, N.A. DiOrio, X. Li, J. McLaren, Impacts of valuing resilience on cost-optimal PV and storage systems for commercial buildings, Renewable Energy, 127, 2018, 896-909,ISSN 0960-1481.

4 Moving Beyond Li-Ion

Moving beyond 4-hour duration also raises the question of the possibility of moving beyond Li-ion batteries as the (nearly) exclusive stationary energy storage technology currently being deployed. There are many storage technologies under various stages of development and deployment, and it is difficult to estimate which of these technologies will achieve cost reductions at scale. However, it is possible to demonstrate the types of cost and performance improvements necessary to achieve parity with Li-ion at various durations.

Figure 15 (top) shows the estimated power- and energy-related capital costs for Li-ion batteries from the moderate projection in the 2023 ATB.[56] The total capital cost of the storage device (measured in $/kW, which is a standard measurement of power plant costs) is shown in Figure 15 (bottom). This is the power-related cost plus energy-related costs ($/kWh, where kWh means the physical capacity to store one kWh) [57] multiplied by duration of storage in hours. The cost at zero hours represents the cost associated with the power conversion equipment. The slope of the curve represents the energy-related costs, and expected cost reductions reduce the slope of the cost curve over time. It should be noted that there are a wide range of estimates, complicated by recent supply-chain issues, which have produced significant volatility in costs.[58]

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[56] NREL. "Annual Technology Baseline." https://atb.nrel.gov/.
[57] Represents usable energy, after accounting for state of charge limitations, conversion to AC, and other factors.
[58] Cole, Wesley, Akash Karmakar. (2023). *Cost Projections for Utility-Scale Battery Storage: 2023 Update*. NREL/TP-6A40-85332.

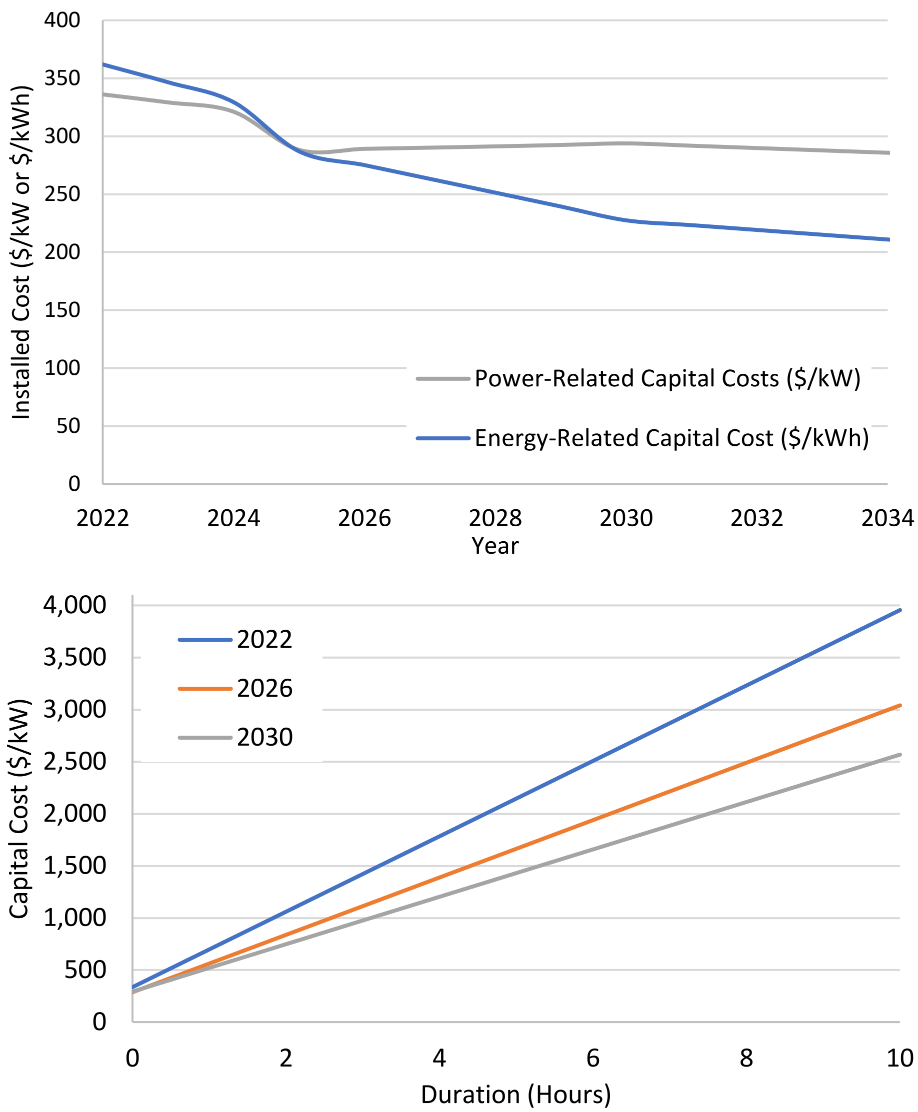

Figure 15. The power- and energy-related costs of Li-ion batteries (top chart) are expected to decline over time, with greater cost reduction expected in the energy-related components. The total cost (bottom chart) is the power-related costs plus the energy-related costs multiplied by duration.

The near-term challenge for alternative storage technologies moving beyond 4-hour duration is competing with the potential cost reductions for Li-ion, which can also be deployed with durations longer than 4 hours. For example, using the 2023 Annual Technology Baseline (ATB) moderate assumptions, the cost of a 4-hour battery today is about the same as the estimated cost of a 7-hour battery in 2030. So as the value of 4-hour Li-ion decreases, it is possible that the storage technology that replaces 4-hour Li-ion could simply be longer-duration Li-ion. Alternatively, there are a number of technologies that have the potential to achieve cost parity with Li-ion batteries. There are four main elements associated with achieving breakeven/effective cost parity with Li-ion: power costs, energy costs, lifetime, and efficiency.

The main opportunity for non-Li-ion energy storage technologies to achieve cost parity is the use of lower per-unit-energy cost storage materials. The energy-related capital costs of a storage device consist of the material that physically stores the energy and the container that holds that material. Li-ion battery electrolytes use a variety of materials and involve a complex manufacturing process, which achieves relatively high energy density and round-trip efficiency, the former being particularly important for vehicle applications. Advanced battery technologies may use lower-cost and earth-abundant electrolyte materials, with less complex manufacturing. This often results in lower energy density, but this is less important for stationary applications than for vehicles. One example is liquid electrolyte flow batteries, which have the potential to use low-cost materials stored in tanks that can be scaled to various sizes; this approach could even be used to scale durations over time, starting with shorter durations, and adding tanks as duration requirements increase.

There are a large number of non-battery storage technologies that can use even lower-cost materials as a storage medium. Thermal storage, which has been deployed in concentrating solar power plants, can use very low-cost materials, such as molten salts stored in insulated tanks. There are several thermal storage technologies being developed for grid storage.

PSH uses an even lower-cost storage medium (water), where the cost of the container (reservoirs) becomes the dominant energy-related cost. Next-generation compressed air energy storage may use a combination of free (air) and low-cost (thermal storage) medium using underground formations.

The trade-off of using lower-cost energy-related materials is often higher power-related costs and lower round-trip efficiency. For example, flow batteries may use lower-cost electrolytes, but require more complex power conversion equipment, including membranes and pumps. Many battery technologies that use earth-abundant or low-cost electrolyte materials have substantially lower efficiencies. Mechanical systems—including thermal, pumped storage, and compressed air—require pumps, turbines, and generators, which in aggregate are considerably higher cost compared the inverter and other power-related components of Li-ion batteries. Mechanical-based systems also have substantially lower efficiency.[59][60]

Alternatively, most mechanical-based storage systems can last much longer and not suffer from cycle-induced degradation. There are many examples of operating pumped storage plants more than 50 years old that have the ability to be upgraded with newer, more, and efficient equipment, while Li-ion systems have an expected lifetime of 10–20 years.[61] Thermal storage and compressed air energy storage are based largely on traditional generation equipment that often

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[59] U. Helman, B. Kaun, J. Stekli. (2020). Development of Long-Duration Energy Storage Projects in Electric Power Systems in the United States: A Survey of Factors Which Are Shaping the Market. *Frontiers in Energy Research* 8.
P. O'Connor et al. (2020). "Hydropower Vision A New Chapter for America's 1st Renewable Electricity Source",https:/doi.org/10.2172/1502612.
Augustine, C., N. Blair. *Storage Technology Modeling Input Data Report*. NREL/TP-5700-78694.
[60] Albertus, P., J. Manser, S. Litzelman. (2020). "Long-duration electricity storage applications, economics, and technologies." *Joule* 4, 21–32.
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lasts 30 years or more. Flow batteries do not suffer from the same degradation mechanisms as Li-ion batteries, and have the potential for relatively low-cost electrolyte replacement.

Figure 16 illustrates how these four factors can be considered to estimate a breakeven cost for an alternative storage technology, or the point at which the technology achieves life cycle cost parity. In this figure, the Li-ion cost curve for 2030 (from Figure 15) is shown in blue. A hypothetical alternative technology with higher power-related costs and lower energy-related capital costs is shown in gray. In this example, the alternative technology achieves capital-cost parity at 6 hours, and therefore is the lower (capital) cost option at any durations of 6 hours or longer.

However, capital-cost parity is not the same as life cycle cost parity, which is impacted by technology efficiency and service life. If the performance of the alternative technology is the same as Li-ion, then capital-cost parity would be the same as life cycle cost parity (black dot). But longer-lived technologies reduce the life cycle cost of projects because they can be financed over longer periods. This means, all other factors being equal, longer-lived mechanical and alternative battery-based storage could have higher capital costs than Li-ion and achieve life cycle cost parity. Alternatively, reduction in efficiency would mean an alternative storage technology would need to have lower capital cost to achieve cost parity because it would yield lower energy time-shifting value.[62]

[62] The loss in efficiency impacts energy time-shifting value but generally not capacity value, which tends to create the largest amount of value for storage. The significant caveat to this statement is that there is a lower bound to the efficiency where capacity credit begins to be impacted. There must be sufficient time to recharge between discharge cycles, and this recharge time increases with decreasing efficiency. An 8-hour device with an 80% round-trip efficiency requires 10 hours to fully charge. But an 8-hour device with a 40% efficiency requires 20 hours to charge. So, this device cannot serve repeating 8-hour long peak periods, and therefore would likely not have the same capacity credit as one with a higher efficiency.

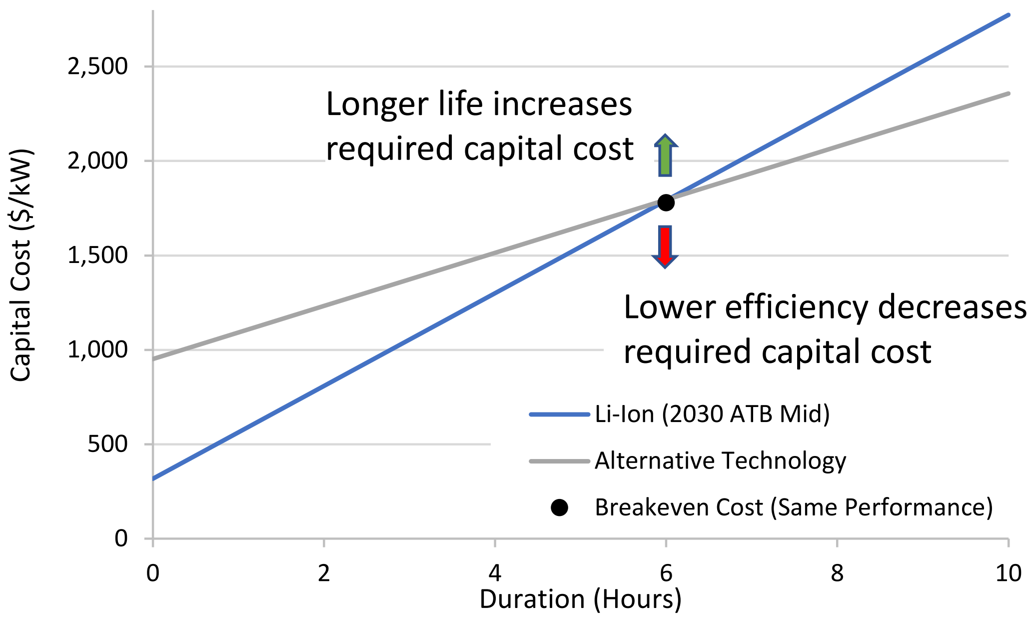

Figure 16. Conceptual life cycle breakeven conditions for an alternative storage technology showing the impact of capital costs and how project life and efficiency can increase or decrease the capital costs required

While Figure 16 shows a single alternative technology, there may be a family of curves with different technologies achieving a lowest life cycle cost for various durations. However, it is important to note that just because a technology becomes the lowest cost at some duration does not mean it will be economically viable. As costs increase, storage becomes less competitive with alternative (non-storage) options for power system flexibility and capacity. So there are limits to how far it may be possible to move along the least-cost envelope illustrated in Figure 16 and still continue economically deploying longer and longer-duration storage.

Despite this caveat, a large range of possible combinations of power- and energy-related costs can achieve cost parity with Li-ion, particularly at longer durations. Figure 17 provides an example, showing the energy-related costs needed to achieve cost parity for an 8-hour device as a function of power-related costs using 2030 assumptions for Li-ion (15 year life, 85% efficiency, and 2023 ATB moderate cost assumptions).[63] The lowest black line shows the breakeven curve for a technology that has the same life and efficiency as Li-ion, with the actual assumed costs shown in the black square using ATB moderate assumptions. Any combination of power- and energy-related costs that results in costs at or below the black line would achieve cost parity.

The other curves show breakeven conditions for alternative technology performance, including longer lifetimes and lower round-trip efficiencies. As before, breakeven cost means that the alternative storage technology costs must be at or below the respective line for the three different efficiency levels, with Li-ion shown for reference. This comparison assumes only capacity and energy time-shifting values, where adjustments to the time-shifting value correspond to a

[63] Assuming a 5% interest rate and a 15-year life with zero salvage value produces a 9.6% fixed charge rate.

roughly 2% decrease in time-shifting value for every 1% decrease in efficiency.[64] The 30-year life reduces the annualized cost by about 32% compared to a 15-year life.[65] This example assumes that both technologies have the same perceived risk in terms of capital financing, and similar costs of operation and maintenance. Overall, even with lower efficiencies, the longer-lived technology can be more costly and still achieve cost parity with Li-ion.

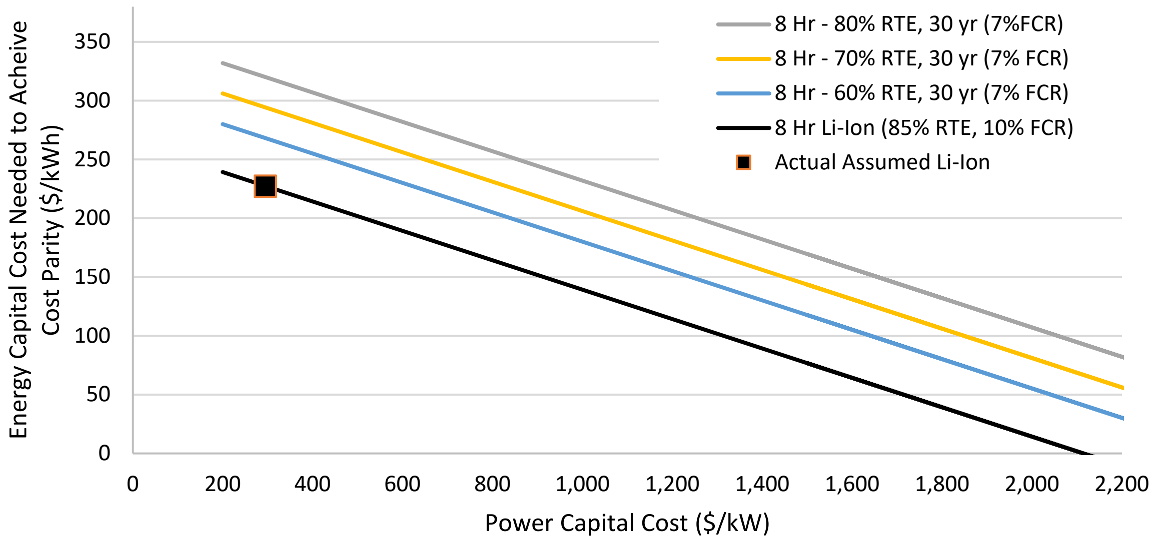

Figure 17. Alternative storage technologies can achieve life cycle cost parity with an 8-hour Li-ion technology in 2030 (represented by the black line) with a large combination of possible power- and energy-related capital costs. Energy-related capital costs must be at or below the lines shown for various technology performance assumptions, and capital costs can be higher than Li-ion for technologies with longer service lives, even after the impact of lower efficiency.

This demonstrates that it is possible to achieve cost parity with Li-ion for longer durations via several pathways. This will likely depend on some combination of longer life and lower energy-related costs, to compensate for potentially higher power-related costs. Several analyses provide additional discussion of costs of a function of duration for various storage technologies and potential opportunities to reduce these costs.[66,67,68]

[64] Sioshansi, R., P. Denholm, T. Jenkin, and J. Weiss. (2009). Estimating the Value of Electricity Storage in PJM: Arbitrage and Some Welfare Effects. *Energy Economics*. 31, 269-277.
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5 Discussion and Conclusions

Li-ion batteries represent about 99% of all stationary storage being deployed in recent years, and more than 90% of these batteries have durations of 4 hours or less. This reflects both the state of the technology, and the strong influence of the current market duration requirements for capacity, which results in a significant decline in value beyond 4 hours of duration.

Opportunities for moving beyond Li-ion and beyond 4 hours of duration in the near-term then requires changes to both technology and the value proposition. On the technology side, several options have the potential to achieve lower per-unit of energy storage costs and longer service lifetimes. These could offset potentially higher power-related cost and lower efficiency to achieve life cycle cost parity at some duration. On the value side, the value of 4-hour storage is likely to drop over time as many regions in the United States shift to net winter peaks. This would increase the relative value of longer-duration storage that would be needed to address the longer evening peak demand periods that cannot be served directly with solar energy. Opportunities for storage to support transmission and resilience could also increase its value.

Previous analysis in the Storage Futures Study identified economic opportunities for hundreds of GW of 6+hour storage even without new policies targeted toward reducing carbon emissions.[69] Achieving economic deployments of longer-duration storage will require changes to current incentive structures, particularly in wholesale market regions. This includes monitoring and changing marginal capacity credits for additional storage as appropriate to send proper signals to potential developers, as well as resolving issues related to monetization of services across different use cases, particularly related to services traditionally provided by rate-of-return compensation.[70]

Finally, it is important to recognize the challenges faced by emerging technologies competing against the well-established Li-ion technology. The market for Li-ion batteries is growing at a fast pace, driven largely by electric vehicles. This will create new innovations and the potential for cost reductions in stationary applications. Reaching cost parity for new technologies will depend on achieving deployments at scale. Continued support could help enable a diverse portfolio of cost-optimal storage technologies with durations that vary to support the evolving grid.

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[69] Blair, N., C. Augustine, W. Cole, P. Denholm, A.W. Frazier, J. Jorgenson, K. McCabe, K. Podkaminer, A. Prasanna, B. Sigrin. (2022). *Energy Storage Futures: Key Learnings for the Coming Decades*. NREL/TP-7A40-8177935.

[70] JB Twitchell, JD Taft, R O'Neil, A Becker-Dippmann Regulatory Implications of Embedded Grid Energy Storage April 2021 https://energystorage.pnnl.gov/pdf/PNNL-30172.pdf